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SUMMARY REPORT

on

FEASIBILITY STUDY OF 2000 FOOT UNDERWATER BREATHING APPARATUS

to

NAVAL COASTAL SYSTEMS CENTER

August 14, 1978

by

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ABSTRACT

In this research program the feasibility of developing an underwater breathing apparatus (UBA) for use at depths in the 2000 foot range was studied. It was found that every presently known system has inadequacies that would preclude its efficient use at such depth, but that combining some of the features of the present UBA's could result in a useful apparatus.

It was found that a backpack mounted scrubber, with integral gas heating and PO2 control, with a fan-driven circulation system, could be interfaced with the present Mark 12 diving apparatus to produce a UBA that would satisfy the operational requirements.

FOREWORD

This report summarizes research conducted on the feasibility of developing an underwater breathing apparatus (UBA) for use to depths in the 2000 foot range. The work was performed from September, 1977 to August, 1978, under Contract Number N61331-77-R-0004 for the Naval Coastal Systems Center in Panama City, Florida. J. W. Grimes, Jr. served as project monitor for NCSC while Battelle's principal investigator was P. S. Riegel.

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INTRODUCTION

The United States Navy has developed a large number of underwater breathing apparatus (UBA) for its use in a wide variety of operational situations. Myriad operating principles are employed depending on the requirements of the situation. In addition to the UBA themselves, support facilities, including ships, saturation diving systems, and decompression procedures have been developed to support the man in the water. Attention has been focused on the thermal problems as well, and diver heating systems have been and are being developed.

Although Navy divers have dived in the open sea to over 1100 feet, and in chamber dives to 1500 feet, the equipment used on these dives was not designed for hard work at such depths, and workloads and dive durations were strictly regulated so as to keep the conditions within the capability of the life support equipment.

The present depth limitation of Navy diving equipment is 1100 feet, using the Mark 14 closed-circuit saturation diving system (CCSDS). This equipment, although tested successfully to its limit, is still in the process of development. The Swimmer Life Support System, Mark 1, (SLSS) has also been used at great depths, but the breathing resistance inherent in such an apparatus will probably restrict its fully operational use to depths less than 1000 feet.

Although some other diving organizations have performed limited open-sea operations to greater depths, the equipment used was such that it would probably not be suitable for use under the extremely demanding conditions which must be anticipated in Navy diving. At present the Navy has no diving capability in excess of 1100 feet.

Because Navy interest may some day extend to the limit of man's physiological tolerance, this feasibility study was contracted to explore by what means Navy diving might be safely extended to a 2000 foot depth.

Submarine or Suit?

There is no question that, in terms of pure life support at deep depths, the articulated suit is without peer. The diver breathes an airlike mixture at atmospheric pressure, he can dress as his comfort dictates, eat, drink, perform eliminatory functions and enjoy all the comforts of existence in a very small, close fitting, anthropomorphic submarine. The two drawbacks to the articulated suit are lack of mobility and tactile sense. The diver cannot lay his hands on his work, nor can he move about freely. He must work with tools alone, and this loss of dexterity and feel makes the articulated suit less versatile on the job.

It has been made abundantly clear that the process of descent and ascent is vastly simpler with the hard suit. Open-sea useful work is now regularly performed with these units by commercial firms.

Still, there is no substitute for the human hand in certain situations. Therefore, while the excellence of the life support qualities of the articulated suit is conceded, still it is desirable to put a man in the water at times when his versatility is needed. Whether the adaptability of "soft" divers is worth the price to be paid in saturation and decompression is a choice to be dictated by operational requirements. A UBA for the "soft" diver will provide such a choice.

SUMMARY

Operational parameters for diving to 2000 feet were established, and currently existing breathing apparatus were evaluated to determine their

suitability for use at that depth. All currently available UBA, with the exception of the articulated rigid suit, were found to be unsuitable for the desired use, because of excessive breathing resistance, excessive gas usage, or mechanical complexity.

A new concept was discovered which holds great theoretical promise. Consisting of a backpack-mounted scrubber with an automatic oxygen control system, it can be attached to present rigid helmets such as the Mark 12. Gas circulation through helmet and scrubber is achieved through use of a high-speed blower. The system uses very little gas and is simple in concept.

The new system, used in the air mode, would permit diving to 200 feet with a 6 scfm, 100 psi air supply, which would offer great operational advantages on vessels of limited compressor/air storage capability.

CONCLUSIONS

During this investigation the following conclusions were reached:

(1) Man-powered gas circulation is not feasible beyond 1000 feet if present medical criteria for respiratory work are to be met.

(2) A forced-circulation helmet is the only presently known means for providing non-diver-powered gas circulation.

(3) Two kinds of forced circulation helmets presently exist:

  (a) Mark 5, Mark 12 -- open-circuit helmets. These are not acceptable because of enormous gas usage.

  (b) Push-Pull -- a good solution to the problem, but not yet developed beyond 1000 feet
   - bigger pumps needed--about twice the present power levels--20 hp to 40 hp.
   - fatter umbilicals are needed to handle additional gas flow.

(4) A new type of closed-circuit apparatus shows great theoretical promise. It can be built as a backpack attachment to the Mark 12 helmet.

RECOMMENDATIONS

As a result of the foregoing conclusions it is recommended that:

(1) A program to develop a backpack fan scrubber be initiated. The first part of the program should focus on the development and construction of an air-mode unit for use at depths to 200 feet. This will provide a UBA that can be evaluated for comfort, operational ease and practicality in pool tests without need for saturation diving techniques.

Once the practicality of the air mode has been demonstrated, a PO2 controlled HeO2 model should be built for evaluation at greater depths.

(2) Upon the completion of the development of the initial prototypes, several copies of each should be made for further evaluation by Fleet units.

(3) The Navy should protect the concept by whatever patent coverage is possible, to prevent the Navy from being deprived of manufacturing rights in the event of parallel development by civilian firms.

OPERATING REQUIREMENTS AND MISSION SCENARIOS

At present there is no clearly defined mission for a scuba having a 2000 foot capability. Infinite uses may be conjectured, but the capability of such a rig is still well in advance of the medical research and diving experience of any potential users. The 2000 foot depth figure is even an approximation. The figure could as well be 1500 feet or 2500 feet. The choice is somewhat arbitrary but the approach for designing the new UBA will be the same regardless of the specific depth chosen as the design target.

It is likely that the duration of use will be four to six hours. This is a long enough time for the diver to accomplish useful work but not so long as to burden him with consumables (i.e., gases, scrubbers, batteries, etc.). The diver will need to be kept warm, and his breathing gas heated.

Respiratory work will need to be minimized, and the existing target of 1.7 Joules per liter will serve as the goal for this deep UBA as it has for shallower apparatus.

INTERFACING WITH EXISTING PROGRAMS

In developing a new UBA for use at 2000 feet, it is not necessary to design every part of the apparatus anew. There are numerous existing diving apparatus that may be used to good advantage in the development of the new UBA. In discussions of where the new apparatus would fit in among current Navy development efforts, a rough outline of the existing NCSC development efforts was evolved. Those areas where the new apparatus would fit in were also defined. It is shown in Figure 1.

It can be seen from Figure 1 that a considerable portion of the work that would ordinarily be required in developing a UBA has already been done. We need only concentrate on those areas that relate specifically to the increased depth. Diver heating, especially as it relates to diver dress, is presently being addressed in ongoing NCSC programs. Gas heating, control of partial pressures, gas circulation and interfacing with existing equipment comprise the remainder of the development task.

BACKPACK FAN-SCRUBBER

Shown in Figure 2, the backpack fan-scrubber is basically a back pack attachment, designed to be worn with a diving helmet/constant-volume dry suit.

The unit is an externally-powered circulatory device that removes carbon dioxide laden gas from the diver's helmet, removes the carbon dioxide from the gas, replenishes the oxygen consumed by the diver, heats the gas to a suitable temperature, and reintroduces the gas to the helmet where it may then be breathed by the diver.

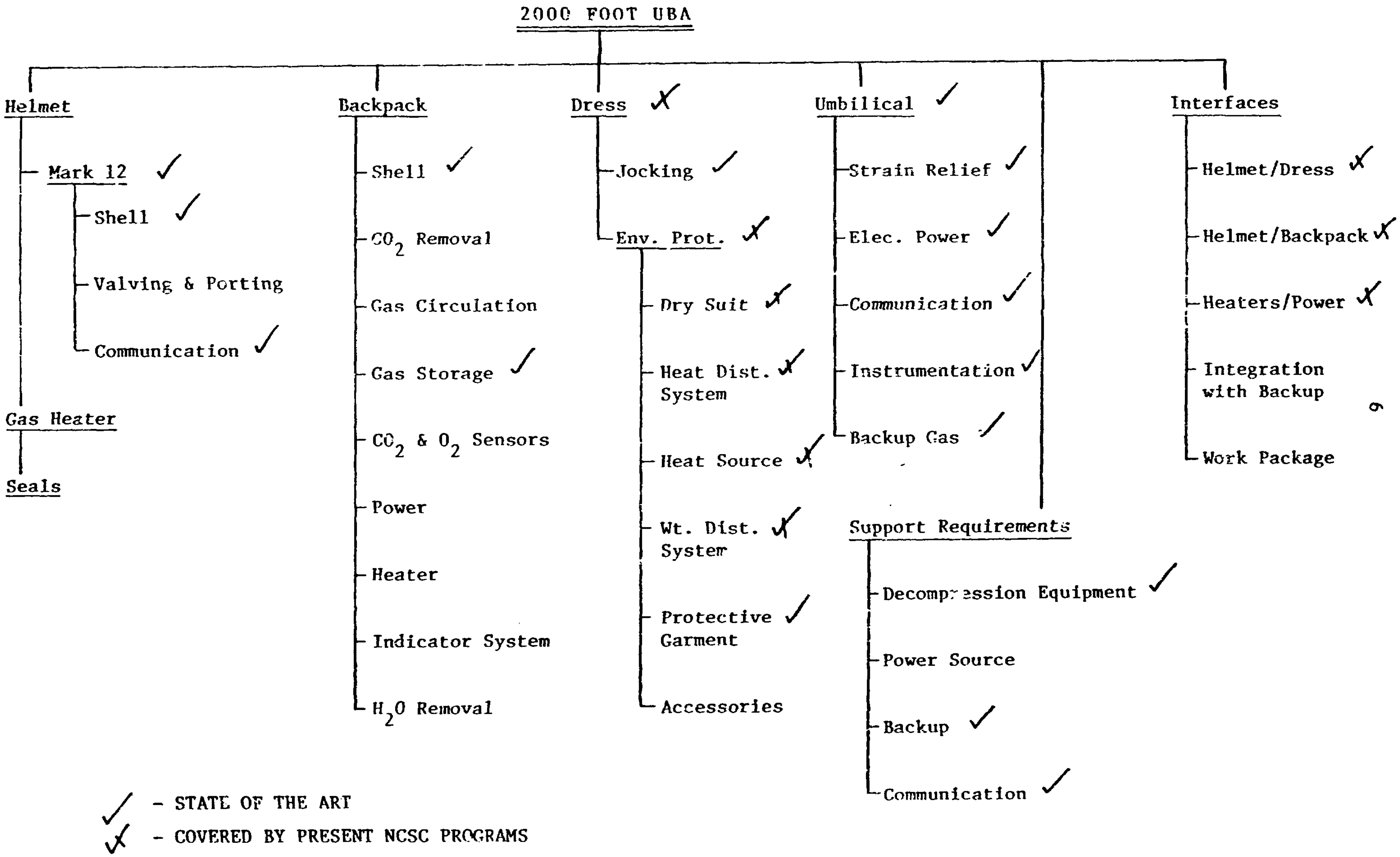


FIGURE 1. EXISTING PROGRAM INTERFACES

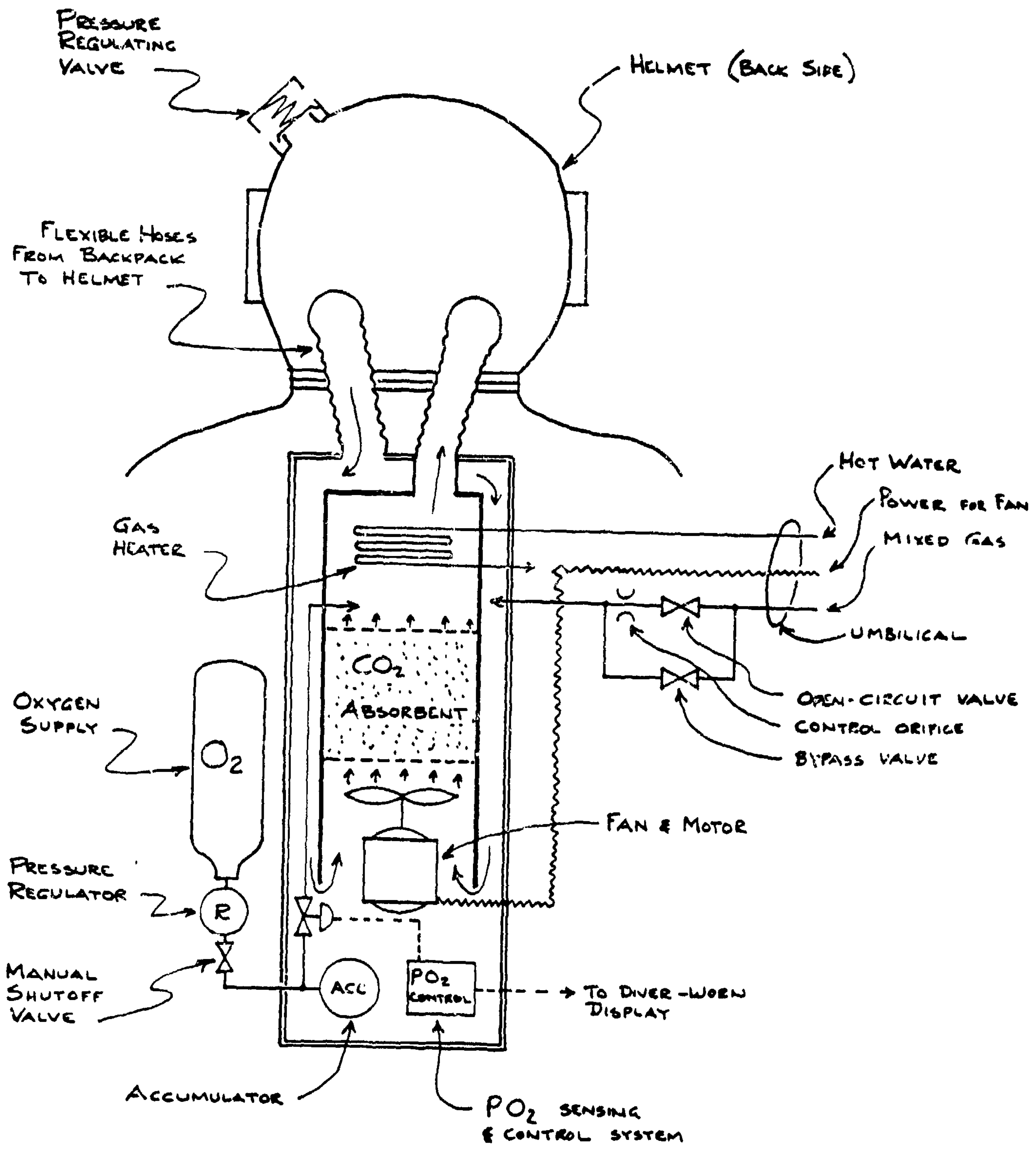


FIGURE 2. BACKPACK FAN-SCRUBBER SCHEMATIC

The backpack is connected to the helmet by means of two flexible hoses that permit relative movement between helmet and backpack, for diver mobility and comfort.

A dry suit with neck ring connected to the helmet is used to gain the necessary flexible volume for extreme tidal volumes and minute volumes employed by the diver when working hard. The helmet may also be used with a neck seal, but it will greatly lose effectiveness when so used, because of the limited stroke of the neck seal.

The primary mode of operation is closed circuit. Diluent gas, for maintaining suit inflation to the desired level, is brought in through an umbilical hose. Once the suit is inflated to the desired level, use of further diluent gas will be minimal. Oxygen is supplied from a backpack-mounted oxygen flask, through a regulator and accumulator, to a control valve. An oxygen sensor and controller opens the control valve periodically when the oxygen partial pressure reaches a predetermined low value. The accumulator is sized so that the amount of oxygen that is introduced will not elevate the oxygen partial pressure above a previously determined level.

A motor-driven fan circulates the gas across a bed of carbon dioxide absorbent. The gas is heated by means of hot water coils or an electrical resistance grid, and then enters the helmet.

In an emergency, the diver may shut off his oxygen and open up a valve on his diluent line, to use diluent gas in an open-circuit mode. The diluent gas will contain a small, but life-sustaining amount, of oxygen. The bypass valve, located in parallel with the open-circuit valve, is spring-loaded so that it closes when the diver is not holding it open.

A pressure relief valve, mounted at a suitable location (shown here on the helmet) allows gas to vent from the suit while the diver is ascending or in the emergency open-circuit mode.

The chief advantage of this apparatus is that it allows the diver to operate in the constant-volume suit mode, with very low breathing resistance, because the diver need not use his respiratory system to pump gas around the circuit. This apparatus is also much simpler and cheaper than either open-circuit (which wastes vast quantities of gas at extreme depths) or conventional push/pull systems, which require massive hardware at the personnel transfer capsule or other diver refuge.

The Backpack

The backpack of the fan-scrubber should be about the same size as that presently used with the Mark 12 helmet in the venturi-driven semiclosed-circuit mode. It would contain a fan, a scrubber, muffler, gas heater and all gas valving and partial-pressure control devices. In all likelihood it would consist of a fiberglass backboard on which the components are mounted, to which can be attached a protective fiberglass cover. Strapping arrangements would be identical to those of the Mark 12 backpack.

The Scrubber

If we assume an average CO2 production rate of 1.5 lpm, a six hour mission duration, and a Baralyme efficiency of 50 percent (0.195 lb CO2 absorbed per lb Baralyme), a scrubber of 300 cu in is required. This volume may be attained using a scrubber of 5-inch diameter by 15-inch length, or by any number of other configurations. In general, it is preferable to keep bed length to a minimum so as to decrease gas velocity through the bed and thus minimize pressure drop. Bed shape will have no effect on retention time.

It is certain that the gas entering the scrubber will need to be heated if the desired efficiency is to be achieved. Every scrubber study to date has demonstrated that scrubbers fail miserably when used with cold gas. Since the gas must be heated for diver respiration, anyway, this requirement is not particularly troublesome.

Gas Heating

The circulated gas must be heated, both for diver safety and for scrubber efficiency. So long as hot water suits are used, the most straightforward means of heating the gas would be by means of small hot-water heat exchangers, located at the scrubber inlet and at the gas outlet from the backpack. This assures that the gas will be heated as close to the points of thermal need as possible.

As a second option, the entire backpack may be easily flooded with hot water, eliminating the need for internal heat exchangers. This means also allows the hoses connecting the backpack to the helmet to be heated, by covering them with loose-fitting polyethylene tubes connected to the main body of the backpack. This approach, while attractive mechanically, is thermally inefficient because of probably high heat losses through the walls of the backpack.

Electrical heating of the gas is an obvious third option. Since a power line will enter the backpack to operate the fan, it could easily be tapped to provide resistance heating to the gas stream.

Final choice of heating options would be premature at this time.

The Helmet

The Mark 12 helmet has been thoughtfully provided with connections for a venturi-driven semiclosed-circuit backpack, intended to operate in a similar manner to that on the Mark V helium-hat deep sea rig. These connections would form an excellent interface with the backpack fan-scrubber. It is not known at this time whether the connections are of sufficient size as to minimize pressure drop in the circulation loop. Excessive pressure drop in the loop will require greater fan power than if components are sized for low flow losses, but a compromise between size and power required must be eventually struck. However, this problem is most appropriately addressed during the development stage of the backpack fan-scrubber.

In all probability, the Mark 12 helmet will be able to serve as the helmet of choice for the 2000 foot UBA.

Diver Dress

The dress of the Mark 12 is adequate to the needs of the proposed system. The dress should be used in the constant-volume mode, with the helmet gas space connecting directly with the interior of the suit. This will add volume to the gas bubble in which the diver breathes, and because the area for expansion and contraction is greater in the shoulders of the suit than it is in a neck seal, the diver may take a deep breath.

In a neck seal, the volume of the system can change only as much as the seal can move. Typically this is from 1 to 2 liters, which is insufficient for hard work. A counterlung could be added to the system, but the constant-volume suit has been used successfully for well over a century and it is a simpler way to achieve the compliance necessary in a closed-circuit system.

Oxygen Control

Control of the partial pressure of oxygen in the system can be achieved in exactly the same way as it is presently controlled in existing closed circuit scuba, such as the SLSS Mark 1. This technology is well-developed and readily adaptable to the specific needs of the 2000 foot UBA. It is likely that certain pressure-sensitive parts of the system, such as sensors, battery packs and circuitry will have to be examined and modified for the increased depth, but the technology is presently state-of-the-art with no obvious obstacles.

Gas Circulation

In sizing a fan to circulate the gas an estimate of the flow resistance of the system must first be made. The best of the recirculating scubas is the SLSS Mark 1, on which Battelle conducted flow vs. pressure drop tests in an effort to reduce breathing resistance.

It is expected that any flow circuit to be designed would have flow resistance of the same order as this unit, so its characteristics will be used for estimation purposes. In a prototype SLSS, fitted with a low-resistance mouthpiece, it was found that the flow resistance of the system, from the inlet of the exhaust hose, through the scrubber and case, to the outlet of the inhalation hose, amounted to 13.3 cm of water at a measured air flow of 11 cfm at atmospheric pressure.

For a flow of 6 cfm, the pressure drop would have been 3.96 cm water, or 1.56 inches, since pressure drop is proportional to the square of flow. Therefore, we seek a fan that can move 6 cfm at 1.56 inches of water fan total pressure. Because output of the fan will remain theoretically constant if size and speed are unchanged, the fan that will move air against the head developed at the surface will also be able to circulate the denser gas at depth. The power required at depth, however, will be greater.

The ability of a fan to deliver a volume of gas against a given head is a function of its "Total Euler Head", which in turn is dependent on the fan's diameter and rotational speed. For our particular requirement of 6 cfm at 1.56 inches of water, theoretical fan speeds and sizes are as follows:

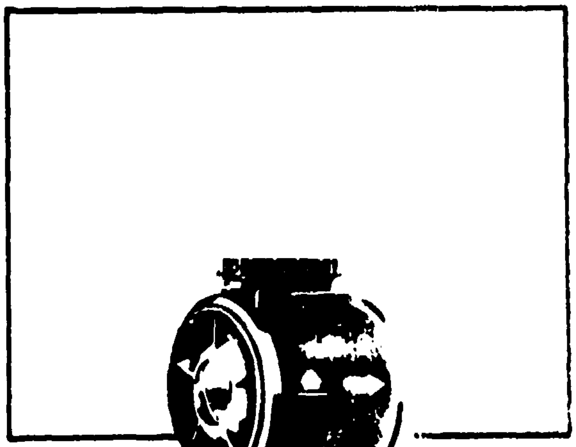
RPM	Fan Diameter, Inches
900	15.3
1,200	11.5
1,800	7.6
2,400	5.7
3,600	3.8
10,000	1.4
20,000	0.7

It is obvious that a high rotational speed will be required if a fan of reasonable size is to be used. Fortunately, numerous small, high speed fans are available on the market. Reproduced herewith is the specification sheet for one such fan that comes close to meeting the requirements of our system. The Aximax 1 vaneaxial fan, by Rotron, Incorporated can produce 6 cfm at 1.6 inches of water, while operating at 22,000 rpm. This would suffice for most conditions of hard work.

Although the Aximax, in a standard trim, would suffice to do the job at atmospheric pressure, the increased density of the gas would require added power. For a PO2 of .6 ATA at 2000 feet, a system oxygen content of about 1 percent is required. The density of such a mix is about ten times that of atmospheric air. Therefore, the power required to turn the fan at depth on HeO2 would be about ten times that required at the surface using air. It is doubtful that the motor presently supplied integral with the fan would be adequate. A new motor would be required, but such development

Aximax 1 VANEAXIAL FAN

ROTRON® INCORPORATED



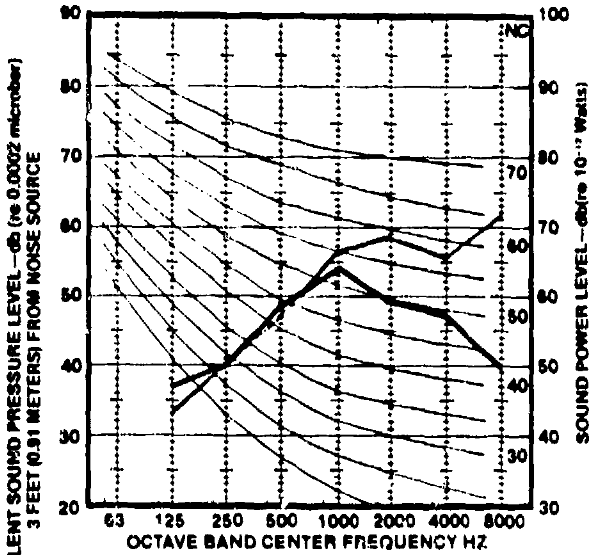
FEATURES

- 10 - 21.5 CFM (4.72 - 10.15 L/Sec) 11,000 - 22,500 RPM • 400 Hz
- Size - 1.50" dia x 1.75" length (38.1 mm x 44.4 mm)
- Weight - 4 oz (0.113 kg)
- 115 vac - 1 phase • 400 Hz
- 200 vac - 3 phase • 400 Hz
- Meets applicable military specifications

APPLICATION

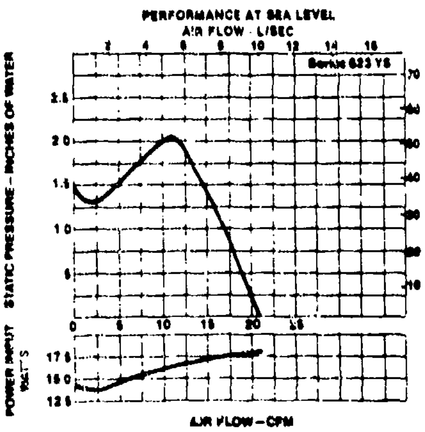
Most compact of its series, Aximax 1 is ideal for tightly packaged airborne electronic equipment where size and weight must be held to an absolute minimum. The Aximax 1 will deliver 17 CFM (8.02 L/Sec) of cooling air against a resistance of 1" (25.4 mm) w.g., operating reliably for many thousands of hours in ambients of − 54°C to + 125°C

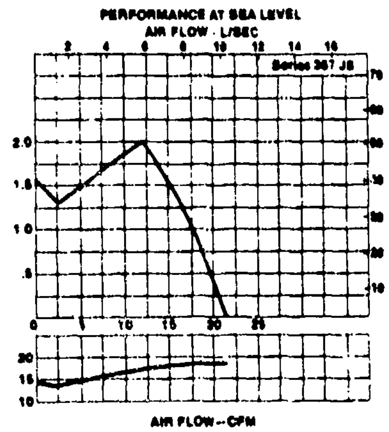
Acoustical data was obtained in Rotron's reverberant room sound test facility, permitting accurate determination of sound power level (PWL) referenced to 10^{-12} watts. For easy comparison with other published data, the left hand ordinate of the graph shows the calculated equivalent sound pressure level (SPL) at a distance of three feet (0.91 meters) from the Aximax 1 fan. The SPL figures may be correlated with the NC contours shown to determine the NC rating.



LEGEND	FLOW (cfm)	FLOW (l/sec)	NOMINAL SPEED (rpm)
———	7.0	3.3	11,000
- - -	14.0	6.6	22,500

- Impeller Blades–Airfoil construction for maximum aerodynamic efficiency
- Bearings–Stainless steel, ABEC Class 5
- Barrel Assembly and Impeller–Cast aluminum, dull jet black enamel finish.





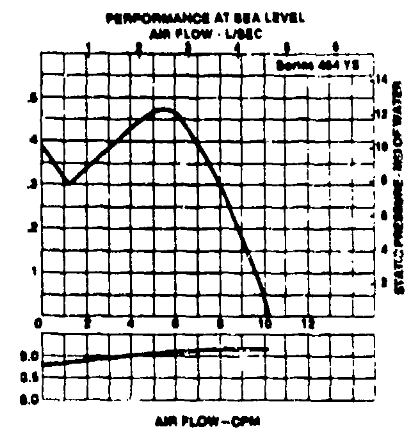
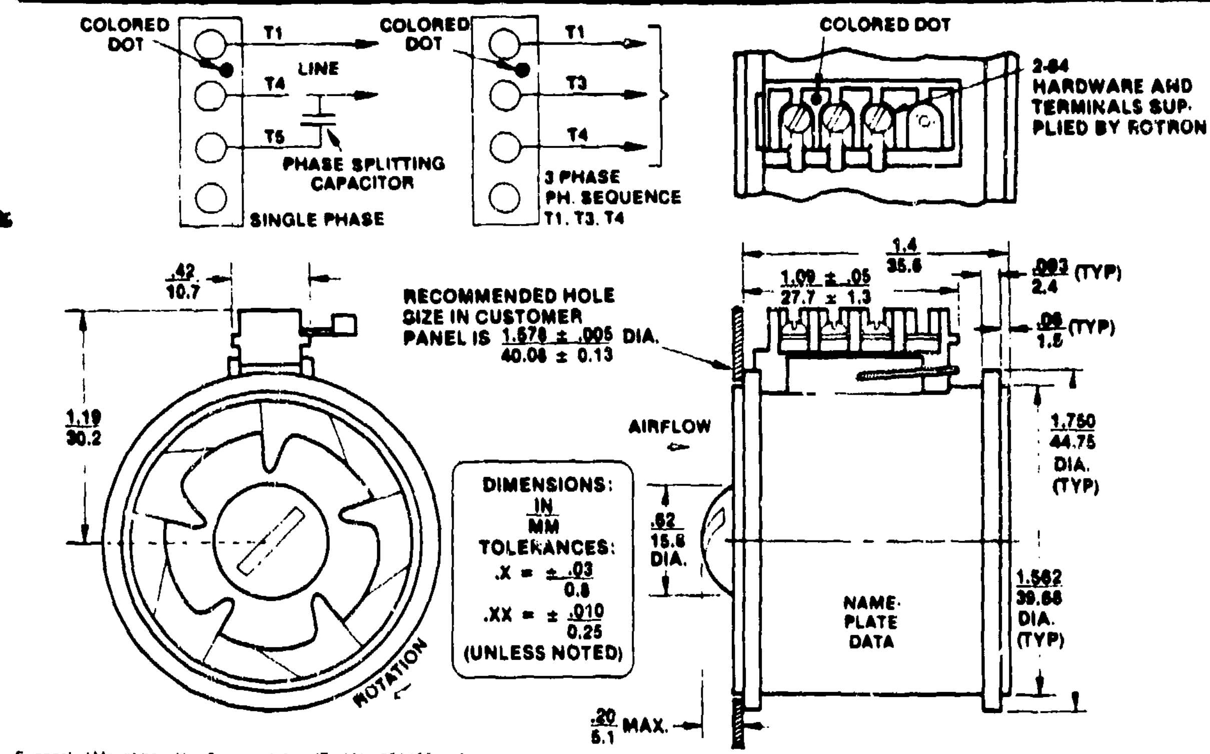


FIGURE 3. FAN SPECIFICATION SHEET



Suggested Mounting—Use 3 servo clamps (Part No 271167) or 3 reverse mount servo clamps (Part No 271166) installed on a 2 031 / 51 59 diameter Specifications subject to change without notice

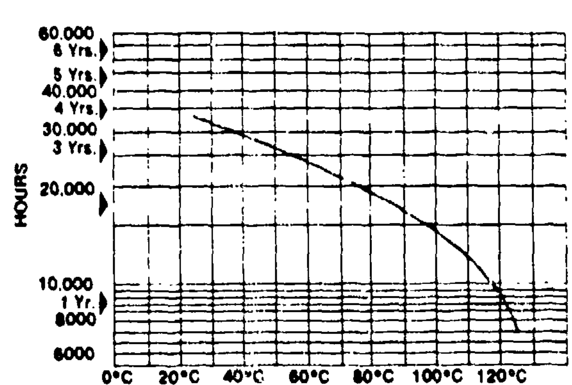
MOTOR

- Induction motor available in three standard series
- Insulation—Class H
- Double shielded stainless steel ball bearings
- Integral grease reservoir for long, maintenance free life

SPECIFICATIONS

Series	Part No	Volts	Ph	Hz	Cap ' Mfd.	Watts	Line Amps	Locked Rotor Amps	RPM	CFM	L/Sec	Max Amb. °C
623YS	026942	115	1	400	0.25	18.0	.16	.40	22,000	21.0	9.91	125
367JS	026493	200	3	400	—	18.0	10	.30	22,500	21.5	10.15	125
464YS	026944	115	1	400	0 15	9 0	10	.17	11,000	10.0	4.72	125

A[illegible] figures are nominal free de[illegible]very values at [illegible] [illegible] 202 kg cu m density
Running capacitors not supplied by Rotron



LIFE EXPECTANCY

The curve represents the continuous duty life for the Aximax fan at a given temperature after which 90% of the units will still be operating. This data was obtained by statistical analysis of fans run at various ambient temperatures and a speed of 22,500 rpm

ACCESSORIES

Servo clamps—Part No. 271167
Reverse mount servo clamps—Part No. 271166

ROTRON INCORPORATED

ROTRON INC.
AN EG&G COMPANY

Woodstock, N. Y 12498 ☐ 914 • 679-2401 ☐ TWX 510-247-9033
Garden Grove, Cal 92641 • 714•898-5649 • Rotron B.V., Breda, Netherlands. Tel (076)879311, Telex NL 54074

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FIGURE 4. FAN SPECIFICATION SHEET

would be relatively routine. The fan would operate on 115 or 200 Volt, 400 Hz power. The Aximax is not suggested as the ultimate fan, but is included to show that such small, high capacity fans are presently state-of-the-art.

Control of fan sound will be an important part of the development task. As shown in the Rotron sheet, the example fan has an equivalent sound pressure level of between 50 and 60 db when operating in air. When operating on HeO2 at depth, the level will be about 20 db higher. This will require that the fan be well-provided with sound insulation, and that the gas station be provided with mufflers on either side of the fan.

Shallow Operations

The backpack fan-scrubber can be used from the surface to 200 feet if air is substituted for mixed gas. In the shallow mode, compressed air is supplied to the apparatus at about 6 scfm. This flow rate will permit hard work at 200 feet while keeping the oxygen content of the respired gas to a level near 20 percent, thus minimizing decompression problems. A far lower flow of air could support hard work, but only at greatly reduced oxygen partial pressures.

The 6 scfm flow is also adequate to support the diver in the emergency open-circuit mode, in the event that his circulator fan should fail.

The existence of the backpack fan-scrubber would allow many surface support ships to operate to depths which, at present, they cannot reach because of compressor or air supply limitations.

For dives that are deeper than 200 feet, the apparatus may be used with appropriate HeO2 mixtures in the semiclosed mode, and will have far less gas consumption that a Mark V or Mark 12 used in the venturi circulation mode.

TYPES OF BREATHING APPARATUS STUDIED

In order to gain knowledge of available technologies in UBA development, all types of UBA extant were examined and compared to see which parts of the existing apparatus would be suitable for use, in total or in part, in a

2000 foot UBA. Although every single specific apparatus has not been mentioned the generic types have been included and it is believed that every type of apparatus in existence today will fall into one or another of the categories selected. A description of each type of UBA follows.

Mask and Snorkel

This item of breathing equipment is included only because it is the simplest and most reliable type of breathing apparatus that can be used while using any breathing apparatus at all. It is obviously unsuited for the task at hand but is included in the matrix only for purposes of comparison.

Closed Circuit Oxygen Rebreather

This type of apparatus, the closed circuit oxygen shallow water rig, is typified by the Emerson and Drager rigs used by underwater demolition teams and combat swimmers. It uses pure oxygen in a recirculating mode with a carbon dioxide scrubber. Gas is powered through the system through the efforts of the divers' respiration. It is limited in use to a depth of 30 feet, principally because to descend beyond this depth invites oxygen toxicity. It is limited in duration to about 3 hours, principally because this is the approximate life of the carbon dioxide scrubber. This rig is not suited for diving to great depths and is included, as was the Snorkel, simply for purposes of comparison.

Open Circuit Scuba

Open circuit scuba is perhaps the most common type of diving apparatus in use today. While generally employed at depths less than 130 feet, there is no theoretical reason why the traditional demand regulator cannot be employed to any depth desired. It is, of course, understood that to employ open circuit scuba at greater depths will involve trade-offs, principally with economy of gas flow and the necessity for designing the ports and passages much larger to accommodate the enormous gas flows involved at great depths. In addition, it is questionable whether, when using conventional cylinder gas supplies, the gas, when used at 2000 feet, can exit the storage cylinder fast enough to supply open circuit scuba. Again, there is no theoretical reason why open circuit scuba cannot be used but it is probably not a good choice for this particular use.

Band Mask

The band mask is now authorized for Navy use and has acquired a good record in shallow water use. It has also been proven for use at great depths, having been used as deep as 1500 feet on some Navy dives. However, its principal drawback, as with open circuit scuba, is the relatively enormous amount of gas required to use the unit at great depths.

Open Circuit Helmet

The open circuit helmet is the most common type of breathing apparatus used by commercial divers today. It is used in its traditional mode as typified by the Mark V hard hat, and in its modified configuration as shown by the Mark 12 and by numerous commercial helmets which are similar to the Mark 12. It is rugged and simple, and there is no theoretical reason why it could not be used at 2000 feet. However, gas flow is enormous and this alone would preclude its use by a rational operator, except in dire emergency.

Venturi Recirculator Helmet

This rig is typified by the Mark V and Mark 12 helmets, used with their backpack mounted scrubbers. Also, some commercial helmets have been equipped in this way. This mode of operation was developed because it was early seen by operators that the advantages of open circuit helmet operation could be enjoyed with less gas usage if some of the gas were to be recirculated. The amount of gas used, however, at 2000 feet is still quite large and may be considered prohibitive for use. The duration of use of recirculator helmets is anywhere from 3 to 8 hours depending on the design of the scrubber which is used. The duration of use may be extended in emergency situations by going to the open circuit mode but this, of course, places a great burden on the gas supply.

Semiclosed-Circuit Rebreathers

These types of breathing apparatus enjoyed great vogue in the late 60's and early 70's just before the advent of the more sophisticated closed circuit backpack rebreathers. They are typified by the Navy's Mark VI, Mark VIII and Mark IX rebreathers and also by a number of foreign rebreathers, principally those manufactured by Dragerwerk AG. They generally employ a critical flow orifice to supply gas at a constant rate to the diver. The gas is of such a composition that its oxygen partial pressure is not higher than can be tolerated by the diver and it is supplied in such quantity that sufficient oxygen for heavy work is available to the diver, without depressing the oxygen level in his breathing bags. Although the gas consumption and simplicity of this sort of apparatus are quite attractive, it has the drawback of high breathing resistance at 2000 feet and of a fairly limited duration of use because of the design of the scrubbers.

Closed Circuit PO_2 Controlled Rebreathers

This type of apparatus is typified by the Biomarine CCR-1000, the SLSS Mark I, The Navy's Mark 11, and by the Beckman/Starke electrolung. It is an apparatus in which a backpack mounted scrubber and a resilient breathing bag is used to permit the diver to recirculate his breathed gas. It also employs an oxygen sensor, which triggers a valve to admit pure oxygen to the rig whenever the partial pressure gets below a certain desired level. The shot of oxygen administered is such that the total system oxygen partial pressure does not go higher than a certain desired level when the shot is completed. Various readouts are provided with the rig to permit the diver to know the value of his oxygen partial pressure at any time. This type of apparatus uses very little gas. In theory, only the oxygen itself is consumed by the diver. Its duration is limited by the life of its scrubber, and its breathing resistance is high because of the presence of corrugated hoses and unidirectional check valves through which the gas must be pumped by the respiration of the diver.

Arawak

This type of early push-pull system was developed by Westinghouse in the 60's during the SeaLab experiments. It consists of an umbilical supply and return line and a diver-worn set of shoulder mounted breathing bags. Each breathing bag is supplied with a demand valve. The right hand shoulder bag has an inhalation valve which admits gas to the right hand shoulder bag when the bag level gets below a certain level, which would happen when the diver inhales. When the diver exhales, he inflates the left hand shoulder bag which in turn triggers an exhaust valve which allows gas to be sucked from the shoulder bag. Exhausted gas is returned to a helium reclaimer for scrubbing. This type of apparatus uses considerable gas. However, the gas can be reclaimed at the surface. Therefore, arguments can be made that it consumes little gas. However, if used at a very deep depth the relatively high flow of gas would put great strain on any reclamation and supply system. In addition, the breathing resistance of this apparatus at 2000 feet is likely to be quite high.

Cousteau Push-Pull

This type of apparatus was built by the Cousteau organization for use in his Conshelf series of dives in the early 1960's. It consists of a supply hose, a return hose, and a chest mounted demand regulator which serves to regulate both inhalation and exhalation flow of the diver. While technical information on this apparatus is not available, its concept is elegant and there is no reason why, with good engineering, it could not serve as well as the Arawak system as a type of primitive push-pull. Its advantages and its drawbacks are similar to those of the Arawak.

Conventional Push-Pull Systems

These systems are typified by the Navy's Mark XIV, The La Spirotechnique EIP-5, and by various other push-pull systems employed by commercial operators. In the push-pull system the diver operates from a PTC and gas is supplied to him and returned from him via a special pump. The diver does not wear a scrubber on his back because the gas that is brought to him is the same gas breathed in the PTC by the operator. The gas returned from the diver is discharged to the PTC in the vicinity of the scrubber and thus imposes no greater load on the system than would an extra operator within the PTC. This type of system requires fairly powerful pumps to push and pull the gas to and from the diver but enjoys the special advantage of extremely low gas consumption and quite low breathing resistance because a full helmet may be used. Breathing resistance can be virtually nonexistent if the helmet is used with a conventional seal to the suit, thus leaving a small bubble near the shoulders of the suit. Breathing resistance will be somewhat higher when used with a conventional neck dam because of the necessity of moving the neck dam up and down as the diver respires.

JIM/SAM Articulated Suits

These suits enjoy wide publicity today and are an offspring of the Galeazzi and Neufeldt-Kuhnke articulated suits developed in the early part of this century for deep diving. They are an extremely efficient approach to some problems in deep diving because they permit the operator to descend totally enclosed within a one-atmosphere compartment. The operator, therefore, does not need to decompress nor does he encounter any special problems of breathing resistance because the density of the gas which he breathes is the same as the air which he normally breathes topside. The articulated suits, while generally used in a tethered mode, are self-contained and are actually small, special purpose submarines. Buoyancy control is not as sophisticated as in a submarine, but in many respects they are similar. The diver is somewhat limited because of the stiffness of the joints in these suits. In addition, his dexterity is greatly impaired because his hand cannot be exposed to the pressure of the sea water and he must work through manually controlled manipulators at the ends of the suit arms. When the task is known ahead of time and when suitable manipulators can be designed, great savings in diving operation complexity can be realized through use of these suits. However, these suits are outside the scope of this study.

FENZY Semiclosed Circuit Rebreather

This type of rebreather developed in the late 60's by FENZY of France proves to be a great improvement over the conventional sort of rebreather which employs a constant mass flow gas supply. The conventional type of rebreather uses a constant gas supply large enough to supply the most extreme needs of the diver. The FENZY system, however, employs a proportioning bellows within the breathing bag which discharges gas from the system in proportion to the rate at which the diver breathes. This has the advantage of combining the semiclosed system with the demand system and results in savings in gas as well as predictability of operation. Its breathing resistance is likely to be quite high at 2000 feet because of the necessity of the diver pushing gas through hoses and valves.

Backpack Recirculator With Fan and Scrubber

This idea, while presently only a concept, has potential for use at great depths because it can be built far more cheaply than a conventional push-pull system, yet does not have the high breathing resistance of the partial pressure controlled rebreathers. In this type of system, the diver would wear a helmet and the gas would be recirculated through his helmet by means of a fan. A scrubber in the system would remove the carbon dioxide and oxygen would be replenished by means of a valve controlled by an oxygen partial pressure sensor. All gas would be supplied by means of an umbilical and the two mixtures would be provided, (1) pure oxygen for use in a normal mode and (2) a suitable mixed gas, say, 1 percent oxygen, which could be used in the open circuit mode, should the necessity arise. While this rig is not proven in service and has never been built, no new technology is involved and, of the choices available at present, it might well represent a viable alternative for use at 2000 feet.

Table 1 shows a comprison of these various UBA for use at 2000 feet.

DISCUSSION OF UBA LIMITATIONS

Table 1 contains headings which describe various characteristics of the apparatuses. A brief description of each heading will serve to clarify the context in which that heading is used.

Depth Limit

There are only two rigs in the chart which have an indicated depth limit. While many of the rigs are not traditionally conceived to be usable at 2000 feet, no limit has been applied to their use unless such use is

APPARATUS	DEPTH LIMIT, FT.	GAS CONSUMPTION AT 2000 FT., SLPM	EXTERNAL POWER REQUIRED?	DURATION OF USE, HRS.	PREMIXED GAS REQUIRED?	DIVER MOBILITY	PROVEN USE TO DEEP DEPTHS?	BREATHING RESISTANCE AT 2000 FT.
SNORKEL	1	--	NO	8	NO	GOOD	NO	--
CLOSED-CIRCUIT O_2 REBREATHER	30	--	NO	3	NO	MEDIUM	NO	--
OPEN-CIRCUIT SCUBA	--	1479	NO	8	YES	GOOD	YES	MEDIUM
BAND MASK	--	1479	NO	8	YES	GOOD	YES	MEDIUM
OPEN-CIRCUIT HELMET	--	2772	NO	8	YES	MEDIUM	NO	LOW
VENTURI RECIRCULATOR HELMET	--	277	NO	8	YES	MEDIUM	NO	LOW
SEMICLOSED CIRCUIT REBREATHER—CONSTANT FLOW	--	150	NO	3	YES	MEDIUM	YES	HIGH
CLOSED-CIRCUIT PO_2 CONTROLLING REBREATHER	--	1	NO	4	NO	MEDIUM	YES	HIGH
ARAWAK	--	1479* (Exhaled gas can be reclaimed)	NO	8	YES	MEDIUM	NO	HIGH
COUSTEAU PUSH-PULL	--	1479* (Exhaled gas can be recalimed)	NO	8	NO	GOOD	NO	LOW
CONVENTIONAL PUSH-PULL	--	1	YES	8	NO	MEDIUM	YES	Low with suit interface Medium with neck dam
JIM/SAM ARTICULATED SUITS	--	1	NO	24	NO	POOR	YES	LOW
FENZY SEMICLOSED CIRCUIT REBREATHER	--	148	NO	4	YES	MEDIUM	NO	HIGH
BACKPACK RECIRCULATOR WITH FAN/SCRUBBER	--	1	YES	8	YES	MEDIUM	NO	LOW

TABLE 1. COMPARISON OF VARIOUS UBA FOR USE AT 2000 FEET

actually impossible. Many rigs are not used much deeper than their normal operational depths, not because such use is impossible but because such use is impractical. Since we do not wish to place undue restrictions on the use of any type of apparatus, if it is possible to use the apparatus at an extremely deep depth it is so stated.

Gas Consumption at 2000 Feet

In developing these gas flows, it was assumed that the diver would be working at such a rate as to consume 1 liter per minute of oxygen. This gives a respiratory minute volume of approximately 24 liters per minute. In reckoning the gas flows for demand systems, the minute volume is simply multiplied by the depth in atmospheres. In ventilation of helmets, that amount of ventilation gas which was required to maintain carbon dioxide at less than 2 percent was employed. In the case of semiclosed circuit scuba apparatus, gas flows were obtained from the chart in the United States Navy Diving Gas manual. In calculating the flows in the FENZY semiclosed circuit rig and in the backpack mounted recirculators used with hard hat helmets, a 10 to 1 ratio of recirculation to supplied gas was assumed. Gas flows for greater work rates will be roughly proportional to oxygen consumption.

External Power

This heading was supplied to indicate whether the rig requires external power to make it work. It can be argued that external power is required to compress gas. However, external power was not considered to be represented by this case. Instead, it was considered to be represented by operating machinery, as in the case of the push-pull systems or the backpack recirculator with scrubber. In any eventuality, external power may well be required if only for communications. The diver will certainly use an umbilical at 2000 feet.

Premixed Gas

Many of the apparatus considered do not require any special gas. They either use compressed air or sep[illegible] mixtures of helium, nitrogen and oxygen. There is no particular weight attached to this category but it is included strictly for information purposes.

Mobility

In order for a diver to operate effectively underwater, it must be possible for him to move about effectively. A swimmer with a snorkel is probably as mobile a diver as can be found, followed closely by those wearing scuba tanks or band masks. When gear begins to get heavier, such as full suits and helmets, we move into the medium range of mobility and in the case of the articulated suit, mobility can be considered at best to be poor. Still with this sort of apparatus it is often good enough to accomplish its intended task.

Proven Use

A characteristic which must be given some weight in consideration of the various breathing apparatus is whether they have been proven in the field. None of the rigs have been used at 2000 feet. However, some have been used at depths approaching of 1000 feet. Those that have operated within this area will be considered at this point to be proven for use to deep depths. Such rigs include open circuit scuba, band masks, semiclosed and closed circuit rebreathers, and push-pull systems and articulated suits.

Breathing Resistance

Breathing resistance is one of the most important characteristics of a breathing apparatus. It is a measure of how much work the diver must use simply to breathe. Studies of breathing apparatus used at shallower depths have indicated that a diver breathing through conventional hoses and check valves may expend so much energy in breathing that he will not be fit for anything else. In general, an extrapolation of test results of backpack mounted rebreathers would indicate that breathing resistance at 2000 feet is excessive and moreover is not likely to be cured by enlargement of the breathing passages, at least to any reasonable degree. It is a virtual certainty that for acceptable breathing resistance at 2000 feet a helmet must be used by the diver; moreover, his breathing resistance will be superior if the helmet is sealed to his suit rather than using a neck dam, because this will eliminate the flexure of the neck dam and allow gas exchange with the suit.